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Energy Procedia 74 (2015) 1306 – 1313

Energy
Procedia

International Conference on Technologies and Materials for Renewable Energy, Environment and Sustainability, TMREES15

On Vaporization of a Single Droplet of Diesel Fuel at LPG Fuelled Engine by Diesel-Gas Method

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Abstract

The result of a zero-dimensional one-zone thermodynamic model developed for diesel fuel jets vaporization at diesel-LPG fuelling for an automotive diesel engine are presented. The break-up period of diesel fuel jet, Sauter diameter of drops, mass flow of vaporized substance, drops vaporization time, forming speed of air-fuel mixture, autoignition delay for diesel and dual fuelling are determinate. In the nearby area of air-LPG mixture burns, the increase of in-cylinder mixture forming speed and the level of in-cylinder pressure lead to a decrease tendency for autoignition delay of diesel fuel. The duration of drops vaporization decreases for dual fuelling.

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Peer-review under responsibility of the Euro-Mediterranean Institute for Sustainable Development (EUMISD)

Keywords: LPG cycle dose, autoignition delay, mixture forming speed, Sauter diameter, mass transfer number, jet break-up, droplet vaporization

1. Introduction

In terms of pollution reduction, the Liquid Petroleum Gas (LPG) can be defined as a viable alternative fuel due to the important reductions in exhaust diesel emissions, especially nitrous oxides and smoke, aspects of real importance in the modern content of pollution legislation, [1, 2]. Nowadays, Liquid Petroleum Gas is a worldwide alternative

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fuel used on a large scale for internal combustion engines. For a 1,5 DCI diesel engine from Dacia Logan, at diesel-LPG fuelling at full load regime, the effective energetically specific fuel consumption decreases with 2% at 4000 min^{-1} , [3]. At the same regime, the NO_x emission decreases with 21% at 4000 min^{-1} , [3]. The CO_2 decreases with 8% at 4000 min^{-1} , the unburned hydrocarbon emission decreases with 35...50% and the smoke emission decreases with 50% at 4000 min^{-1} , [3]. Also at other operating regimes important emissions decreasing are achieved. The mixture forming, the heat release, the energetically and pollution performance of the engine are influenced by different vaporization and burning properties of the LPG comparative to diesel fuel. Higher combustion rate of air-LPG mixtures leads to the increase of maximum pressure and maximum pressure rate, with consequences on cycle variability. Thus, the maximum LPG cycle quantity admitted inside the cylinder can be limited for efficiency, mechanical reliability, noise, smooth running reasons. The higher value of autoignition temperature of the LPG, around 481...544 °C versus 225 °C for diesel fuel, [1] can allow the use of excessive values for the compression ratio and may required the use of additives for LPG cetane number improvement or of the diesel pilot injection for air-LPG mixture ignition. The LPG raised vapour pressure assures forming of air-LPG mixtures of higher homogeneity. The higher value of LPG octane number (ON) (ON propane = 111, ON n-butane = 102 and ON i-butane = 94) and laminar flame speed comparable with the one of gasoline (0,46 m/s) makes the LPG a suitable fuel for spark ignition engines, [1]. Starting the combustion into a relative lean high homogeneity air-LPG mixture influences the combustion process and cycle variability. Also, wide inflamability limits of the liquid petroleum gas 2,1...10,4% versus 0,6...5,5% for diesel fuel will influence the combustion cycle variability and may lead to an improvement of the combustion process and of the pollutant emissions, [1]. The necessary speed of direct atomization becomes lower once the density of injection medium increases. Melcumov [4, 5] establish the atomization domains for a specific fuel and a specific type of injector with the nozzle hole diameter of 0,5 mm, in relation with the fuel jet speed and the pressure of the gaseous environment for injection. In the domain of 2...16 [bar], the fuel jet speed varies between 45 and 110 m/s since the pressure of the gaseous medium of injection decreases. Besides the injector design factors, fuel flow speeds and fuel properties the pulverization is also influenced by the state of injection environment, with effects on drops diameter, [4]. Manea and others authors, [6] show images captured by rapid cinematography of a diesel fuel jet aspects in a air environment at different pressures and temperatures of the injection environment (0,980 bar and 25°C, 19,6 bar and 125°C, respectively, 122,8 bar injection pressure). Because of the vaporization processes modification, the changing of jet aspect and characteristics are obvious. The increase of temperature leads to the increase of jet droplets vaporization intensity, [6]. The increase of the gaseous environmental pressure leads to the friction level increase, and to the increase of atomization level. Giffen shows the results of a study, [7] in which the droplets average diameter slightly decreases till the minimum value, from 16,5 μm till 14,5 μm in the area of 5...22,5 bar as pressure for the environmental in which injection occurs, followed by a increase till 16 μm in diameter when the pressure of the environmental for injection increases over the domain of 22...25 bar, [7]. Giffen, [4, 7] affirm that from a specific value of the pressure for the environmental area in which the fuel injection may occurs, the pressure difference that defines the injection decreases and leads to a significant decrease of the fuel jet speed, fact that leads to the increases of the droplets dimensions. Melcumov [5] shows that the variation in gas pressure produce a modification in droplets distribution and since the pressure of the environmental for injection increases, the atomization becomes more fine, [4, 5]. For 275 bar injection pressure and three injection gaseous medias defined by pressures 9,8, 4,9 and 0,98 bar, the most higher percent of fine droplets, of 10 μm , is allocated to the injection gaseous media defined by the pressure of 9,8 bar; for the other gaseous medias the important percent are registered for drops with diameters of 17 μm and 22 μm , respectively. Pimsner, [4, 8] establish in a time interval of 0,1...1,0 [s] the temperature variation of a tetralin drop with the diameter of 1,06 [mm], and establish also the combustion duration of almost 0,5 s in the centre of the drop and at 0,12 mm from the droplet surface, [8]. Fenn presents the variation of diameter for a large droplet of fuel, [9]; initially, the drop dimensions varies slow due to a vaporization achieved only by heat transfer between drop and surround area at the average temperature inside the combustion chamber, followed by rapid dimensions variations due to the amplification of the substance transfer, defined by mass transfer number B, determinate by the presence next to the drop of the flame zone in the moment when the ignition occurs, [9]. Thus, the diameter square of a benzene drop, situated in an environment at 740°C temperature, decreases in a period of time, starting from 0 [s] (injection moment) to 0,7 [s], from 1,6 mm^2 to 1,4 mm^2 , and since the ignition time, in a 1,25 [s] time interval the droplet diameter square significantly decreases from 1,4 mm^2 to zero, [9]. The increase of the temperature in the gaseous environment of the drop at 700, 750 and 800°C,

significantly reduce the processes total time from 2 [s] to 1,6 and 1,4 seconds, respectively. The vaporization of a diesel fuel drop into a gaseous media situated nearby of other burning drops is influenced by the level of pressure and temperature reached in the closed proximity.

2. Theoretical model setup procedure

2.1. Modeling concept

A one-dimensional, one-zone thermodynamic model is developed in order to study the vaporization and combustion processes of diesel fuel drops inside the engine cylinder for a diesel engine fuelled with diesel fuel. Following the modern concept for vaporization and combustion of the liquid fuel particle, Godsave and Spalding, [9, 10, 11, 12, 13], offer calculus relations for a spherical symmetry classic model, with a diffusive combustion inside the flame envelope developed around the liquid particle. The liquid total mass flow, w_s , that fuels the vaporization area and the flame radius are determinate. The variation of the evacuated vapor mass flow from the vapor surface is related with the flame radius variation. The droplets model defines the most possible diameter of the drops and determines the jets break-up time period. The vaporization time for a diesel fuel particle is evaluated in the modern concept for vaporization of the liquid fuel particle, using calculus relations for a spherical symmetry classic model. The vaporization of liquid diesel fuel drops study is the base for combustion study. Inside the combustion chamber the liquid diesel fuel drops receive the heat from the preheated air and from the residual burned gases by convection and also absorb the radiant energy from the combustion chamber walls and the flame, [4]. The heating of the fuel drop begins, it's temperature increases and the evaporation process starts. When the diesel fuel boiling temperature is reached on the droplet surface, at the specific pressure, the vaporisation process becomes intensive, [8]. During the fuel vaporization from jet, the diffusion of the diesel fuel vapours into ambient area leads to the air-fuel mixture forming around the drop at different concentrations. When the temperature of the fuel vapours rise significantly, the combustion may starts in a diesel fuel vapours-air area surrounding fuel drop where the relative rich dosage suitable for ignition starts, [1, 4] and spreads thru immediate outskirts layers. Vaporization phenomena is variable, because during combustion period the reaction zone is moving due to the fuel consummation, the substance exchange being activated by heat convection and becomes intensively due to an accentuated substance exchange process and to a much more active heating of the drops. These chained processes lead to the mass and dimensions reduction of the diesel fuel drops, assuming that at the end of the vaporization process the drop diameter is zero. Initially, the drop dimensions varies slow due to a vaporization achieved only by heat transfer between drop and surround area at the average temperature inside the combustion chamber, followed by rapid dimensions variations due to the amplification of the substance transfer, defined by mass transfer number B , determinate by the presence next to the drop of the flame zone in the moment when the ignition occurs, phenomena being increased at the increasing of LPG dose that burns inside the cylinder. The pressure inside the zone doesn't influence the vaporized substance flow, but the liquid diesel fuel vaporization constant values are influenced by the pressure variation, [4]. In reality, the experimental research's show the influence of pressure on radiation, convection and burning mass velocity. Since the vaporized fuel flow is proportional with the quantity of heat transmitted to the drop surface, result a variation of the heat quantity similar with the pressure variation and also, there is a mutual influence of the vaporization and combustion of the drops in the nearby area of others drops, the drop vaporization constant or drop vaporization time period, being modified by nearby presence of other drops, [4, 14]. Vaporization constant increases with the number of drops per volume and the heat losses to the flame surface decreasing. Further, the vaporization constant decreases because a oxygen lean zone exists. For much more drops the vaporization constant depends by the injector type, droplets distribution, droplets average diameter and by the volume of the space available for combustion. In some combustion chamber zones, nearby the burning of air-LPG homogeneous mixtures, may exists preheated regions in which the air-LPG-diesel fuel vapours may be heated to a superior temperature and from all quantity of heat released during the combustion, a part of it consumed for heating by admixture and for heating by conductivity, respectively, [15]. Local increases in pressure and temperature of the nearby air-LPG mixture combustion zones lead to the increase of mass transfer number which further leads to the increasing of the vaporized substance mass flow on the nearby droplets surfaces. Also, the modification of the in-cylinder gaseous environment density and of thermal conductivity coefficient with the increase of LPG cycle dose, leads to modification of gaseous environmental thermal diffusivity, of diesel fuel drops surface vaporized substance flow increasing and droplets vaporization time duration decreasing. The diesel fuel-air-LPG mixtures formation is analyzed comparative to diesel fuelling for a 1,5 litre direct injection supercharged

engine, type K9K from Dacia Logan. The diesel engine used is equipped with an electronic actuated gas fuelling system, connected with the classic electronic diesel injection system, being fuelled with diesel fuel and liquid petroleum gas by diesel gas method. The LPG cycle dose is injected inside the inlet manifold and electronic controlled by a secondary ECU connected back to back with the main engine ECU.

2.2. Experimental investigation and droplets model conception

The droplets model is developed for a 1,5 litre supercharged diesel engine at 4000 min⁻¹ and full load regime for diesel fuelling and dual fuelling with a percentage of LPG up till 40%. The K9K K792 is a 4 in line cylinders turbo-supercharged diesel engine, defined by 76/80,5[mm] bore/stroke, 18,3 compression ratio, 1461[cm³] swept volume, maximum power 50[kW]/4000[min⁻¹], 1.8[bar] supercharging pressure, 1600[bar] injection pressure of Delphi common rail injection system, Delphi injectors with 0,15 [mm] nozzle hole bore and 5 jets, [4].

The model for fuel drops vaporization study is developed on the following hypothesis, [4], [16]:

- constant radius fuel drop and flame zone are concentrically spheres
- convection and radiation of the hot gases are neglected
- the vaporization process is isobar and developed in permanent regime
- fuel drop temperature is equal with liquid diesel fuel boiling temperature
- heat conductivity coefficient is independent to temperature
- the air and fuel vapours are perfect gases, the values of specific heats being independent to temperature
- concentration and temperature depend on the radius measured from the drop centre

The model use in-cylinder pressure diagrams smoothed and averaged from 50 consecutive cycles and use the general state equation applied for ideal gases for global in-cylinder temperature determination. Coefficient value of the diesel fuel substitute ratio by LPG is established by an energetic substitute ratio, xc [%], which take into consideration the energetic value of the both fuels:

$$xc = \frac{Ch_{GPL} \cdot Hi_{GPL}}{Ch_M \cdot Hi_M + Ch_{GPL} \cdot Hi_{GPL}} \cdot 100 \quad (1)$$

where: Hi_M , Hi_{GPL} represents the low calorific power for diesel fuel and LPG, respectively, in [kJ/kg]. At only diesel fuelling the xc value is zero. The initial fuel speed at spray nozzle escape, by Hiroyasu [8], [16], [17] is defined by relation:

$$u_0 = 3,9 \cdot \left(\frac{2 \cdot \Delta p_i}{\rho_c} \right)^{0,5} \quad (2)$$

and is not significantly affected by the increasing of LPG cycle dose comparative to diesel fuelling.

Assuming that during the fragmentation period of the diesel fuel jet into droplets, the fuel jet speed remains constant and unchanged and constant to the value registered at the spray nozzle escape, the fuel jet break-up period, t_{sj} , [8], [16] can be evaluated:

$$t_{sj} = 28,65 \cdot \frac{\rho_c \cdot d_n}{(\Delta p_i \cdot \rho_g)^{0,5}} \quad (3)$$

where: Δp_i difference between injection pressure and in-cylinder pressure at the injection moment, ρ_g density of the gas inside the combustion chamber, ρ_c density of the injected fuel, d_n injector nozzle hole diameter. Conception of such droplets model imply the definition of the most possible diameter of the drops, d_p . Droplets size, defined by Sauter average diameter, of injected fuel is evaluated with the Hiroyasu and Elkoth correlation, [8, 16, 17, 18]:

$$(d_p)_{med} = 308500 \cdot (\rho_c)^{0,385} \cdot (v_c)^{0,737} \cdot (\sigma_c)^{0,737} \cdot (\rho_g)^{0,06} \cdot (\Delta p_i)^{-0,54} \quad (4)$$

where v_c and σ_c represent the cinematic viscosity and superficial tension of the injected fuel. The obtained values

are around 10 μm and are represented versus LPG cycle dose in the figure 1b. Following the modern concept for vaporization and combustion of the liquid fuel particle, based on a spherical symmetry classic model, with a diffusive combustion inside the flame envelope developed around the liquid particle. Vaporization of the motionless spherical liquid particle is developed in a stationary regime, the temperature of the liquid fuel and the vapor mass fraction around the particle are constant, [4, 16]. The generated heat inside the fuel drop is not taking into consideration by the energy conservation equation, but the delivered heat quantity per time unit is assured by the convection process thru the area of the liquid fuel drop and the heat diffuses into the drop-gas envelope covering assembly considering a substance mass flow. By the mass conserving equation is determinate in consideration of the hypothesis that is no substance source inside the drop-gas envelope element, [16]. From the equation of the energy conservation, the liquid total mass flow, w_s , that fuels the vaporization area is determinate. The convection process that drives the fuel vapors and the diffusion effect are controlling the evacuated vapor mass flow from the vapor surface. Assuming by the surface conditions that the fuel drop radius is equal with the gas envelope radius, around the fuel drop, the mass flow of vaporized substance at the particle area, w_s [$\text{g}/\text{cm}^2\text{s}$], in stationary regime, [4, 16] is defined by:

$$w_s = \frac{\alpha_g \cdot \rho_g \cdot \ln(1+B)}{r_p} \quad (5)$$

B mass transfer number depending on in-cylinder gas temperature, r_p particle radius

Considering a pseudo-stationary regime, with slightly, low modifications in time for particle surface and limit conditions, the vaporization time, t_v [s], can be determinate. In the end the condition of a particle diameter equal to zero exists, [4, 16].

$$t_v = \frac{\rho_l \cdot d_{p0}^2}{8 \cdot \alpha_g \cdot \rho_g \cdot \ln(1+B)} \quad (6)$$

where $\alpha_g = \lambda_g (\rho_g c_g)^{-1}$ thermal diffusivity (c_g [J/g] specific heat, ρ_g [kg/m^3] the density of the combustion chamber gaseous environment, λ_g [W/cm degree] coefficient of thermal conductivity.

The combustion speed is fundamentally dependent by air-fuel mixture forming speed because the combustion periods controlled by chemical kinetic thru the reaction speeds are lower comparative to the period durations of mixture forming, [4, 16]. The diesel fuel jets are formed by drops with uniform diameters and the mixture forming speed [mg/s] is defined by a relation of type:

$$\frac{dm_{cf}}{d\alpha} = C \cdot m_{ij}^{a_1} \cdot m^{a_2} \cdot p^{a_3} \quad (7)$$

were: m_{ij} is the in-cylinder injected fuel mass, m the in-cylinder injected fuel mass and unformed as mixture, p oxygen partial pressure, C model calibration parameter with experimental data's. Generally, the relation coefficients values are $a_1=1/3$, $a_2=2/3$, $a_3=1/4$, [16].

Inside the fuel jet, defined by particles with the Sauter average diameters, the combustion process in identical for all fuel particles autoignition delay duration being influenced by pressure and engine speed, [1], [16]:

$$t_{aa} = 2,5 \cdot p^{-0,009 \cdot \sqrt{n}} \quad (8)$$

the particle diameter being modified by vaporization process. Injected diesel fuel is vaporized, the resulted drops starts to heat, to vaporized, the formed vapours being mixed by turbulent diffusion with the air driven into the jet. In the areas with suitable mixture concentrations, chemical transformations are started and developed till autoignition occurs. Autoignition physical component is depended by engine design and running factors, heating, vaporization and vapours diffusion in the air which depend on pressure and temperature. Diesel pilot injection assure the ignition and the combustion of high homogeneity lean air-LPG mixtures, leading to a local increase in turbulence, pressure and temperature with effects on mixture forming acceleration.

3. Results and discussions

Usually, the particles resulted from the pulverization process have small dimensions, with average diameters between 10 and 20 μm . The obtained values are around 10 μm and are represented versus LPG cycle dose in the figure 1a. For these particles, with diameters that varies from 9,75 to 9,95 μm , the movement of the liquid-gas separation surface has a major impact on the vaporization speed, [4]. The calculus is developed for fuel particles with 10 μm Sauter diameter. At 4000 min^{-1} speed and full load regime, diesel fuel jet break-up period decreases with almost 17,5% for the maximum substitute ratio. For average values of xc the reduction of diesel fuel jet break-up period is around 8,25%, as is presented in figure 1b. Overall, the reducing time of diesel fuel jet break-up, also reduce the forming mixture period with is related with a higher mixture forming speed.

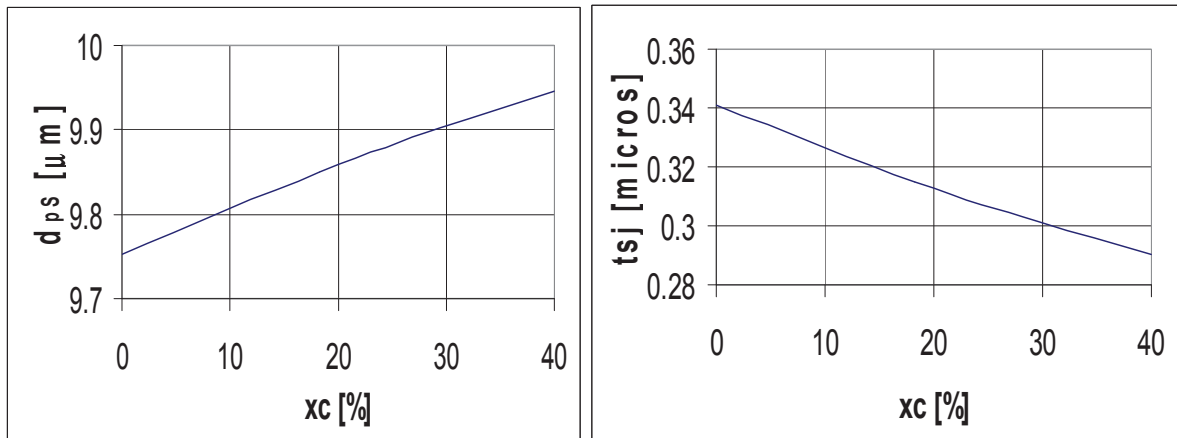


Fig. 1. (a) Sauter average diameter of the fuel drops; (b) Diesel fuel jet break-up period versus substitute ratio at 4000 min^{-1} speed and full load regime.

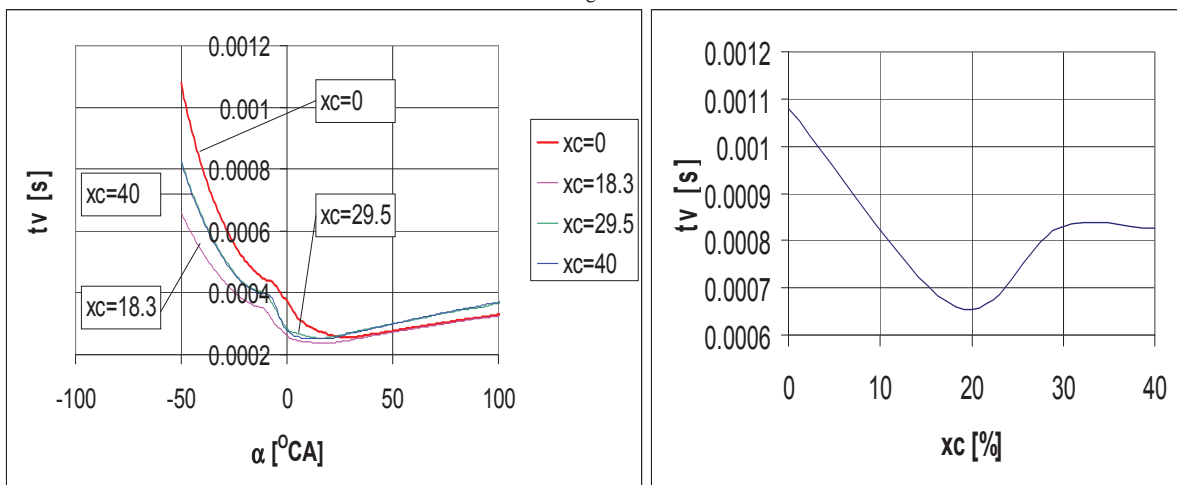


Fig. 2. (a) Diesel fuel drops vaporization period at 4000 min^{-1} speed and full load regime; (b) the maximum of diesel fuel drops vaporization period versus substitute ratio.

The diesel engine is dual fuelled, at 4000 min^{-1} and full load regime, with the possibility of only diesel and diesel-LPG fuelling, at different LPG substitute ratios. For all operating regimes the diesel fuelling is set up as reference and all the measured and calculated parameters in this condition were set up as reference parameters for diesel fuelling engine. The LPG is injected in the inlet manifold, in gaseous state. A relative high homogeneity air-LPG mixture is admitted inside the engine cylinder and ignited by a diesel pilot. The injection and the vaporization

of diesel fuel jets process is influenced by the gaseous medium inside the cylinder which is changing when the LPG cycle dose is modified. At dual fuelling, for all substitute ratios, in interval of $-50 \dots 25$ CA deg., the vaporization time of diesel fuel drops is significant smaller comparative to the reference regime, as figure 2a shows. The maximum vaporization time of the diesel fuel drops shows the reduction tendency for all substitute ratios. For LPG cycle dosages up till 20% the reduction tendency is significantly accentuated and it's almost 70% comparative to classic solution, figure 2b. A slight decrease of vaporization time for fuel drops appears for $xc=30 \dots 40$; for $xc=20 \dots 30$ the smooth increase of only 29% don't exceed the values registered for only diesel and remains in the area of 31% lower comparative to diesel fuelling. Due to LPG gaseous injection, in the inlet manifold are formed relative lean homogenous air-LPG mixtures.

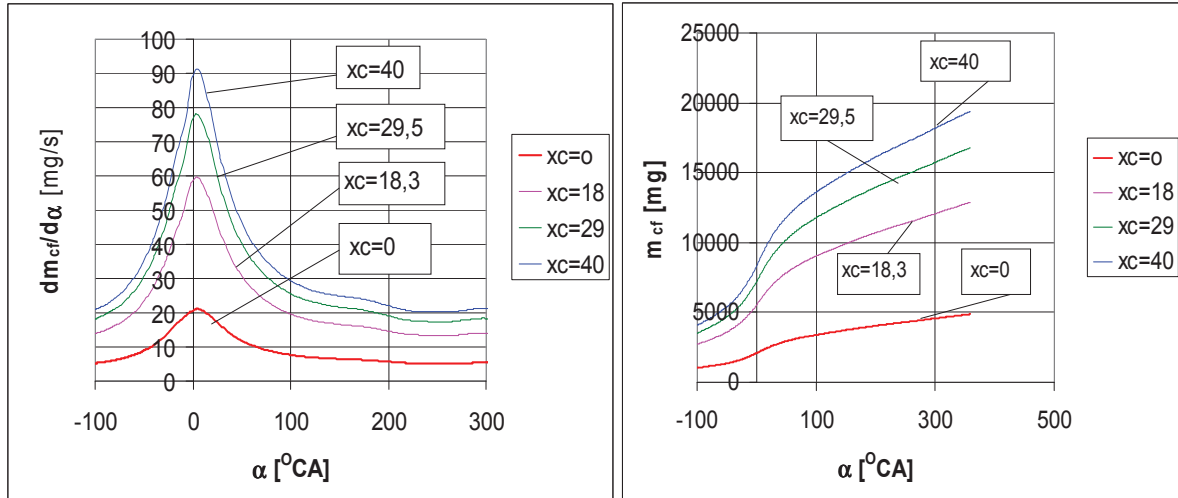


Fig. 3. (a) Mixture forming speed for different LPG substitute ratios; (b) mixture forming law for different LPG substitute ratios for 4000 min^{-1} speed and full load regime.

Diesel pilot injection chemically prepare the air-fuel mixture and assure a reduce pressure rise rate, related with a smooth engine running, and air-LPG mixture ignite. The presence of LPG inside the engine cylinder leads to the increasing of air-LPG-diesel fuel mixture forming speed, as is presented in figure 3a. The acceleration of the vaporization process of the diesel fuel droplets in the presence of the nearby LPG-air burning mixtures also leads to the increase of mixture forming speed and of its quantity during the same interval of time. For LPG substitute ratios bigger then $xc=18$, the mixture forming speed increases and the mixture forming law change its rate of curve, shown an increase in the formed mixture quantity. In the area of Top Dead Centre (TDC) the quantity of formed mixture increases with 125% for dual fuelling versus diesel fuel, figure 4b. Also the forward combustion of homogeneous lean mixtures of air-LPG leads to the increases of mixture forming in terms of speed, not only quantity. Thus, the maximum of mixture forming speed increase with 350% for $xc=40$, 290% for $xc=29,5$ and 200% for $xc=18,3$, respectively. Also, the acceleration of the mixture forming for dual fuelling influences the moments of maximum in mixture formation speed which appears sooner on cycle, closer to TDC, comparative to diesel fuelling, figure 4a. For $xc=20 \dots 30$ the moment of mixture formation speed maximum, is with 27,5% closer to TDC comparative to only diesel fuelling, $xc=0$, at 2,9 CA deg versus 4 CA deg. Injected diesel fuel is vaporized, the resulted drops starts to heat, to vaporized, the formed vapours being mixed by turbulent diffusion with the air driven into the jet. In the areas with suitable mixture concentrations, chemical transformations are started and developed till autoignition occurs. Autoignition physical component is depended by engine design and running factors, heating, vaporization and vapours diffusion in the air which depend on pressure and temperature. Diesel pilot injection assure the ignition and the combustion of high homogeneity lean air-LPG mixtures, leading to a local increase in turbulence, pressure and temperature with effects on mixture forming acceleration. The increase of mixture forming speed with the LPG cycle dose increasing, figure 3, also leads to the decrease of total autoignition delay duration, due to the influence on its physical component. Informative, the autoignition delay decreases up till 10,9% comparative to diesel fuel for $xc=20 \dots 40$, from 0,162 to 0,146 [μs].

4. Conclusions

The developed study marks out the main characteristics of in-cylinder air-diesel fuel mixture formation in the presence of LPG. The main study conclusions are that the break-up period of diesel fuel jet continuously decreases at the increase of the LPG dose, with percents up to 17,5% for the maximum substitute ratio. Droplets average diameter inside the diesel fuel jet is influenced by the density of the gaseous environment inside the combustion chamber, which is modifying with the increase of the LPG in-cylinder quantity, with a low influence on droplets diameter increase of around 2%. The mass flow of vaporized substance on the diesel fuel droplet surface increases up till 2% once with the increase of the substitute ratio, the increasing being associated with the reduction of the droplets vaporization time, with 70% for $x_c=0\dots20$ and with 31% for $x_c=30\dots40$, respectively. The law and speed of air-diesel fuel mixture forming increase up till 290...350% for higher LPG doses $x_c=29,5\dots40$ and with 200% at $x_c=18,3$. The moment when the maximum forming velocity occurs tends to get closer to TDC since LPG dose increases. Diesel fuel autoignition delay, controlled by the in-cylinder pressure level, decrease with 10,5% when the substitute ratio increase. For all diesel fuel substitution ratios by LPG, the diesel drops ignition time decreases comparative to only diesel fuelling regime. The maximum values of ignition times are continuously decrease with 2,4% for x_c values up to 20%, and the further increases of the maximum values with x_c don't exceed the area of the reference regime.

Acknowledgements

The work has been funded by the Sectoral Operational Programme Human Resources Development 2007-2013 of the Ministry of European Funds through the Financial Agreement POSDRU/159/1.5/S/134398.

References

- [1] M. G. Popa, N. Negurescu, C. Pana, *Motoare diesel. Procese*, vol I si II, editura MatrixRom, Bucuresti, 2003
- [2] S.W. Loveseth, I. Snustad, A. L. Brunsvold, G. Skaugen, P. Wahl, K. Y. Lervag, From droplets to process: Multilevel research approach to reduce emissions from LNG processes, *Energy Procedia* 64; 2015, p.3-12
- [3] A. Cernat, *Contributions to the Study of a Diesel Engine Running on Diesel Fuel and Liquid Petroleum Gas*, Doctoral Thesis, University Politehnica of Bucharest, 2010
- [4] V. Pimsner, C. Vasilescu, G. Radulescu, *Energetica turbomotoarelor cu ardere interna*, ARPR, Bucuresti; 1964
- [5] Melcumov T. M. , *Teoria motoarelor diesel rapide*, Editura Oborongiz, Moscova, 1953
- [6] Manea I C, Stratulat M, Munteanu S, Instalatie pentru cercetarea pulverizarii combustibililor lichizi la presiuni si temperaturi variabile, Studii si cercetari de energetica, seria B, XII, 3, 317, 1962
- [7] Giffen E, Muraszew A., *The atomisation of liquid fuels*, Chapman and Hall, 1953
- [8] Pimsner V, Vasilescu C., *Studiul influentei naturii chimice a combustibililor asupra procesului de ardere din turbomotoare*, Seventh Symposium on combustion. Butterworth scientific publications, London, 1959
- [9] Fenn J B., *Lean flammability limit and minimum spark ignition energy*, Fifth Symposium (international) on combustion. Reinhold publishing corporation, New York, 1955
- [10] Kadota T, Hiroyasu H, *Evaporation of a Single Droplet at Elevated Pressures and Temperatures*, Bull J.S.M.E., 19 (1976), no. 138, p.1515-1521
- [11] Spalding D.B., *Combustion of a Single Droplet and of a Fuel Spray*, Selected Combustion Problems. Fundamental and aeronautical applications AGARD, Butterworths Scientific Publication, London, 1954
- [12] Spalding D.B., *Theory of particle combustion at higher pressures*, ASR Journal, 29 (1959), p. 825-835
- [13] Godsave G. A.E., *Studies of Combustion of Drops in a Fuel Spray-burning of Single Drops of Fuel*, 4th International Symposium on Combustion, pp.818, 1952
- [14] Tarifa C. S., *On the influence of chemical kinetics on the combustion of fuel droplets*, CIMAC, Danemark; 1962
- [15] Carпов V., P., *Arderea amestecurilor gazoase in motoare*, Editura Masgiz, Moscova, 1951
- [16] N. Apostolescu, R. Chiriac, *Procesul arderii in motorul cu ardere interna. Economia de combustibil. Reducerea emisiilor poluante*, editura Tehnica, Bucuresti, 1998
- [17] Hiroyasu H, Kadota T., Arai M., *Development and Use of a Spray Combustion Modeling to Predict Diesel Engine Efficiency and Pollutant Emissions*, Bulletin JSME, Vol 26, No.214, pp. 569- 591, 1983
- [18] Elkotb M. M., *Fuel Atomisation for Spray Modeling*, Program Energy Combustion Sci., vol. 8, pp. 61-91, 1982